Towards Efficient Phase Unwrapping*

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ABSTRACT

We present the description of a phase unwrapping technique for interferometric image interpretation. It is based on the simultaneous processing of the original SAR image, the interferometric coherence image and the phase image, to detect areas where the fringes are reliable and may be unwrapped with conventional techniques. Then unreliable areas are treated separately according to their nature as detected by the previous stage: water, urban areas, forests, etc. They are either interpolated or estimated.
Following the demand for more and more accurate topographical information on the earth surface, efficient techniques for phase unwrapping in SAR interferometry are urgently needed to allow automatic interpretation of the signals (Gabriel 1989, Prati 1990, Perlant, 1992). A large variety of methods have been derived in the recent years, which considerably increase the reliability of the develloped phase maps and thus of the derived Digital Elevation Models (DEM). They are roughly based on 3 main categories:

- those which localy integrate phase differences, (Goldstein 1988, Huntley 1989, Prati 1990),
- those which make use of global Fourier analysis, (McGowan 1982, Green 1988)
- those which are based on fringe detection and counting (Lin 1991, Perlant 1992).

Unfortunately, even the most powerful techniques often require human intervention to help or to correct the unwrapping; this human assistance may be desirable to guarantee a high quality of the final product, but, when it is too frequent, it becomes tedious lowering the global quality, and it always remains expensive, since it requires adapted services and hardwares. The purpose of this paper is to present some elements to improve the overall quality of the phase unwrapping stage, based on efficient picture processing techniques. Results are presented on ERS-1 data which have been previously processed to provide interferometric information. These data have been provided by CNES.

1. THE MAIN LIMITATIONS OF EXISTING SAR PHASE UNWRAPPING TECHNIQUES

Conventional phase unwrapping techniques may fail for 3 reasons:

i) - phase wrapping is a non inversible defect for surfaces which are spatially rapidly changing: cliffs, urban areas, layover areas, etc.;

ii) - noise may locally produce discontinuities within coherent areas which cannot be interpreted logically afterwards;

iii) - in some areas, the two original signals may be completely incoherent providing phases which are not reliable at all and cannot be related to the neighbouring area.

There is no solution to solve problem i) without some knowledge on the surface we are looking at. It may appear for instance in the case of a building which may also be interpreted as an empty pool.
Problem ii) received a large attention from the SAR community, and several solutions have been proposed to partially solve it (Goldstein 1988).
Problem iii) is usually considered as non-relevant from phase unwrapping, since it negates the very hypothesis of coherence; thus it has quite seldom be addressed in the literature, although it greatly degrades the practical use of SAR interferometry. Many reasons may cause the SAR signals to be non coherent:

- the signal can be very low and poisoned with electronic noise (it may be the case of water reflection),
- the interfering pixels may poorly overlap because of misregistration,

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- the pixels may contain completely different reflectors (for instance in urban areas, or in case of adverse climatic condition),
- the pixels may contain a variable scattering medium (for instance a forest with wind, or a marsh under variable meteorological or hydrological conditions).

2. GENERAL SCHEME OF OUR PHASE UNWRAPPING TECHNIQUE

The data we are starting from are made of 3 images:

- a) a raw SAR image which may be either one of the two initial images,
- b) a "coherence" image which presents the modulus of the interferometric correlation between the two elements of the pair,
- c) the phase image which contains the wrapped phase of the interferometric correlation.

All these data are quantized on 8 bits; we will refer to them under the names of *SAR, correlation* and *phase* images respectively in the next lines; they are perfectly registered. These data come from two ERS-1 scenes of Ukraine, taken on september 25 and on october 1 1991, with an interferometric baseline of 70 m. They have been processed by CNES, which also performed the geometric registration and provided to us the 3 previous images.

In order to develope the wrapped phase on the largest possible surface of the image, we will proceed in three stages.

At first we detect the areas where the phase is not reliable, and we mask them. This will prevent the phase unwrapping techniques developped in phase 2 to be trapped where no reasonable solution exists. In phase 3, we come back on the masked areas and propose adapted processings according to the nature of each area.

On fig. 1, a flow chart of these 3 stages is presented, where phase 2 has been blown up in two steps.

3. UNRELIABLE PHASE AREA DETECTION

They are several elements which hint at the presence of an unreliable phase area. The most obvious one is a poor local coherence of the phase image: the phase locally appears as a speckled signal. A second indicator is a very low coherence signal. The third one is less pertinent but may be helpful as an additional criterion, it is a poor SAR signal. But a classification based on these criteria doesn't provide a correct detection because SAR signals are inherently noisy, thus such a classification results in a "salt-and-pepper" like distribution. To go past this limit a contextual classification is used. It works in two stages: first a learning stage which allows to measure the class-probabilities, then a classification which makes use of these probabilities to refine a coarse pre-classification by using a Markov random field contextual technique (Geman 1984).

The purpose of the learning stage is to acquire a precise knowledge of the class probabilities of the correlation, the phase homogeneity and the SAR amplitude. This learning stage is nearly automatic. Instead of introducing manually instances of unreliable (label 0) and reliable (label 1) phase areas, the system learns them by itself, either from thresholding the coherence image or from clustering it. The operator task is limited to provide a threshold value or a class-number (the lowest class being attributed to unreliable phase areas). But whatever the designation mode (thresholding or clustering), the learning process cannot be done on the obtained areas because they are too far from reliably representing what an operator would have chosen. Thus the binary image is median-filtered with a large kernel providing a much smoother binary image, and the two largest 0 and 1 components are taken as training areas to determine the class probabilities which will be used in the second stage.

The contextual Bayesian classification used now starts from the raw thresholded correlation image as an initial labelling and improves this labelling using a Potts model of energy to converge iteratively towards a better classification (Wu 1982, Geman 1984). The algorithm which reduces the energy is an ICM descent which is suboptimal but efficient (Besag 1986). The energy has mainly two terms:

- one which expresses the information contained in the pixel and its neighbouring pixels: correlation value, inter pixel phase coherence and SAR value;
- a second which expresses the compactness of the areas we want to obtain; this term is a conventional Potts term counting the number of neighbours with a similar label around the pixel, but it has been biased to reflect knowledge we may have of the a priori probability of the non-reliable phase area.

Using this technique, non-reliable areas are detected accurately in a much better way than with conventional methods. As most of the residues appear in these unreliable phase areas, this also provides an unmasked image with a very low number of residues. We apply to the unmasked image a technique which links positive and negative residues two by two (the *cut* method of (Goldstein 1988)). The cuts are added to the masked areas. Under this light, our pre-processing may be seen as an extension of the masking technique of (Bone 1991).

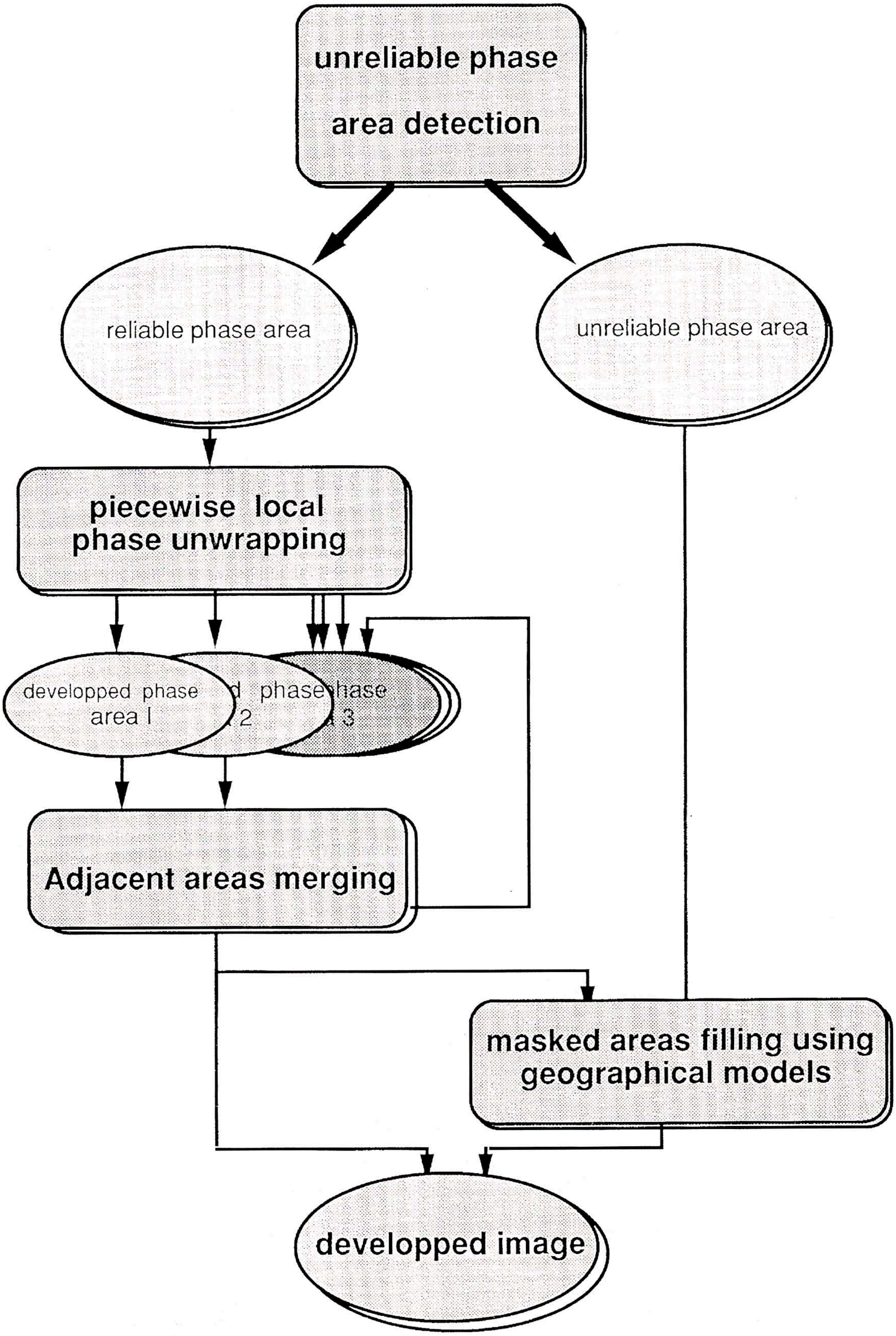

Fig. 1 - Flow chart of the unwrapping technique: the main originality of the method comes from splitting the image in reliable and unreliable areas, which are independently processed. Unreliable areas are treated at a last stage, to guarantee that reliable information will not be poisonned by uncertain or imprecise signals.

4. LOCAL PHASE DEVELOPMENT

In the unmasked area, where correlation is high and phase coherent, we develope the phase, starting from random seeds spread all-over the image. From one seed a propagation is made visiting its four neighbours and attaching to the seed, with the correctly developed phase, every neighbour whose phase difference is lower than a threshold ε (Fig. 2). The threshold ε is chosen, according to the image of interest, so that only the more reliable pixels are aggregated. For instance, in figure 5, e is taken as $\pi/10$. The aggregated pixels are added to the seed, and their neighbours will be visited on their turn. When no other pixel can be added to a seed, another seed is taken and developped.

As a result of this step, many locally coherent patches result, separated by gaps at least 1 pixel wide, but often more. Of course, masked areas remain without phases. The smallest patches (less than 50 pixels) are added to the masked areas (Fig. 3).

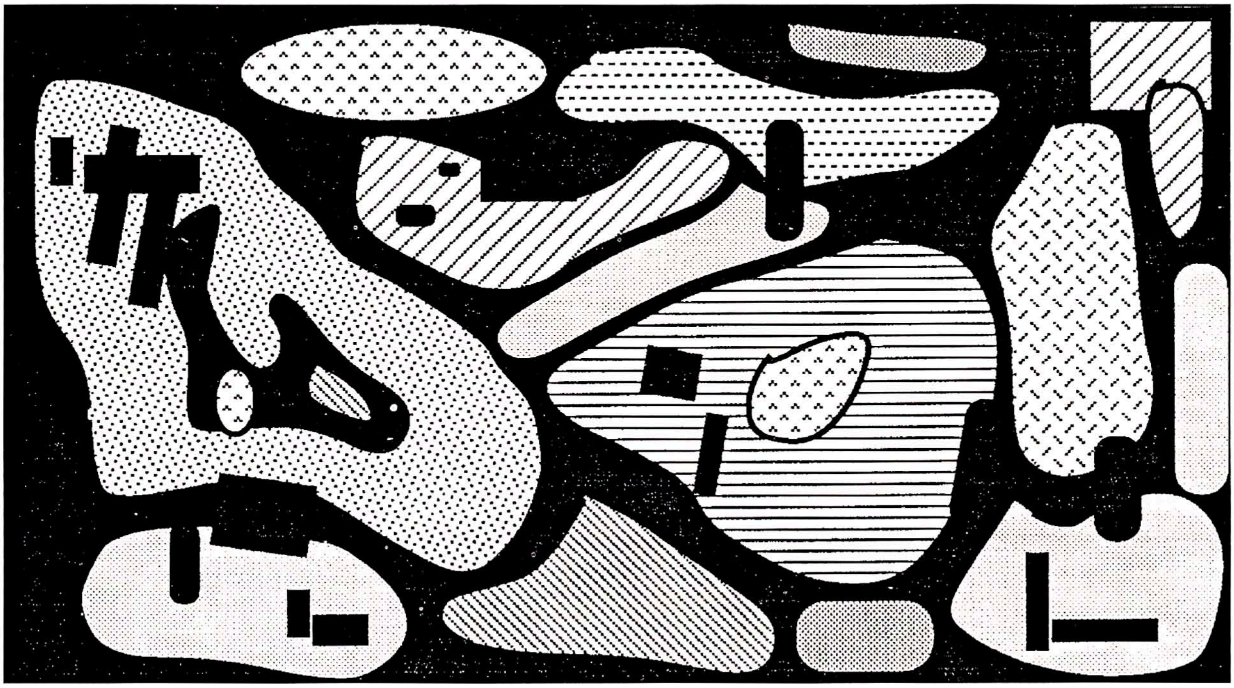

Fig. 2 - From any pixel, a propagation of the phase information is made to develope the reliable areas.

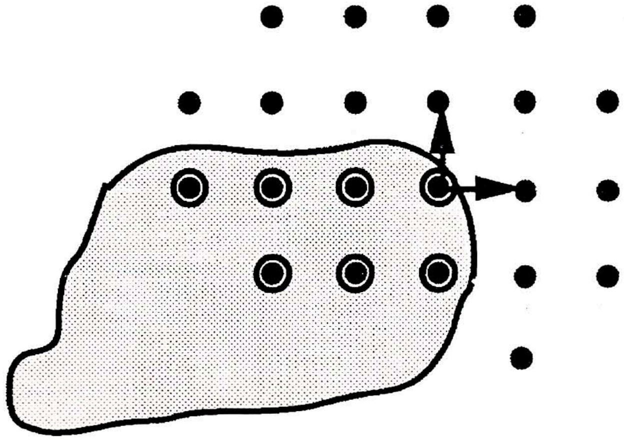

Fig. 3 - As a conclusion of the unreliable area detection stage, the zones were a coherent fringe field exist are marked (textured areas), as well as uncoherent and noisy fringe domains (black areas). According to their size, shape, and statistical properties in the 3 images, these last domains could be roughly classified in categories: fields, rivers, lakes, lay-overs, etc.

Then the local patches are grown, from their borders, by propagating their outmost values iteratively to fill the gaps (Fig. 4). This gap filling stage determines the adjacency between patches, and from the adjacency between patches phases are locked together. This is done by comparing the propagated values where they meet, deciding, from the complete frontier, which multiple of 2π is the most foreseeable.

This step allows to attribute a unique unwrapped phase to every local patch, unless it is completely surrounded with unreliable areas (which is the case for instance with the river separating the image in two mutually uncoherent fields).This stage has been somehow inspired from the method presented in (Gierloff 1987), and could be extended to receive benefits from the graph-theoretic method in (Judge 1992).

Knowing the term which has to be added to every pixel, one can come back on the pixels of the gaps which were not masked. A coherent unwrapped phase may be attributed to them; as they were above the e value with respect to their neighbours, we may suspect the presence of noise, and a Markov random field technique is used to regularize these areas and filter out a possible noise.

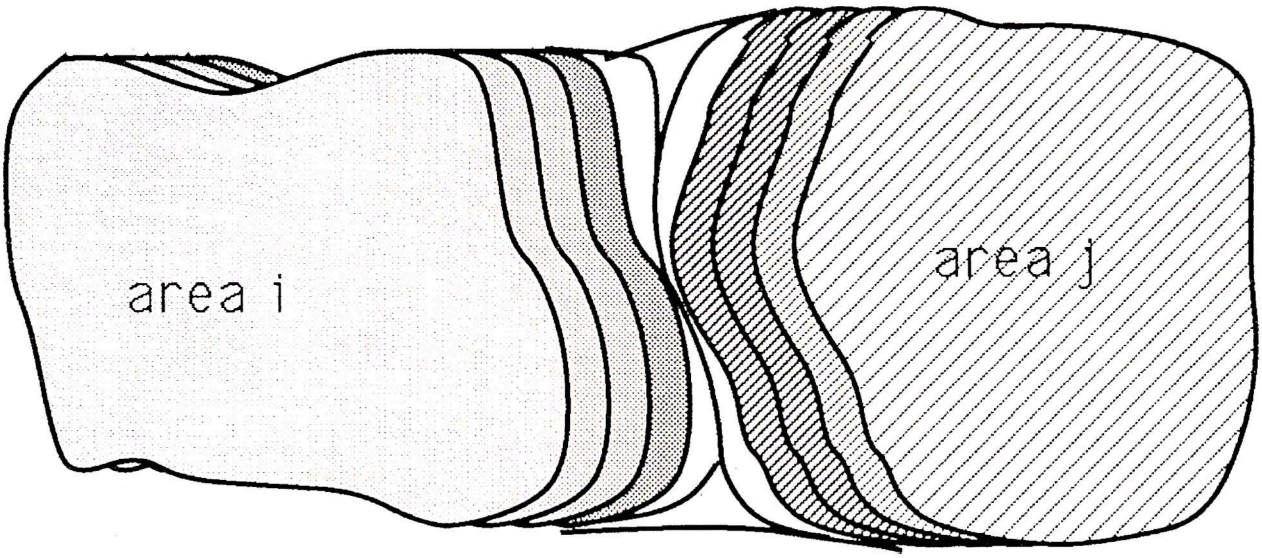

Fig. 4 - When 2 adjacent reliable phase areas are grown, the decision to attribute the exact phase to each of them is made by considering the complete contact front between them, then it is retropropagated to both areas.

5. UNRELIABLE PHASE AREAS TREATMENT

To process the masked areas, we propose that both pattern recognition and geomorphological models be used. Our idea is that masked areas come from many different reasons and should be processed according to their very nature and not blindly. Thus we will suggest, for every zone of a masked area, some interpretation in terms of geomorphological nature: field, wood, river, lake, urban area, etc. And for each type of object an adapted processing is applied. Up to now, only a small number of objects may be detected:

- water since it has a low SAR value, a low correlation and a very uncoherent phase distribution. Water may be divided in lakes and sea or rivers according to its shape;
- fields which may have rather big SAR value, but low correlation and uncoherent phase distribution, but which are geometrically regular,
- forests quite similar to fields, with a lower SAR value, a more uncoherent phase, and often not geometrical,
- urban areas which have very high SAR values, highly uncoherent correlation and phase values, which are not regularly shaped but compact.

In order to recover theses objects, some models have been proposed:

- water is flat horizontal, but rivers which may be slowly monotonous along their longer dimension,
- fields are basicaly at the same level as the ground around,
- the forest height will be measured globally as a whole,
- no information is given on urban areas.

We developed several algorithms to adapt these models, mostly based on MRF and RMS estimations and approximations. Much has to be done in this direction to provide fully satisfactory results.

6. CONCLUSION AND RESULTS

Results of phase development are presented on Ukraine, around the towns of Nikolaiev and Kherson near the Black Sea, on a 120x120 km area. On Fig 5, is presented an enlargement of a small area with the original phase values represented in false colors (5-a), with the unreliable-phase areas masked in black (5-b), the undevelopped phases but filtered unreliable phase areas (5-c), and the final filtered and developped phases (5-d).for the complete image, three stages of our processing are presented (Fig. 7 to 9), along with the original wrapped phase image on Fig. 6: firstly local development of coherent patches on unmasked areas, then the gap filling process which allows to relate phases from adjacent patches when the gaps are not too large, and at last the unreliable phase area treatment, limited here to the fields, woods and urban ares (rivers, lakes and sea are not treated). At the end of our processing (Fig. 9), this image is mainly cut in three parts inside which phases are locally correctly developed, one in the west of the Southern Bug River, a

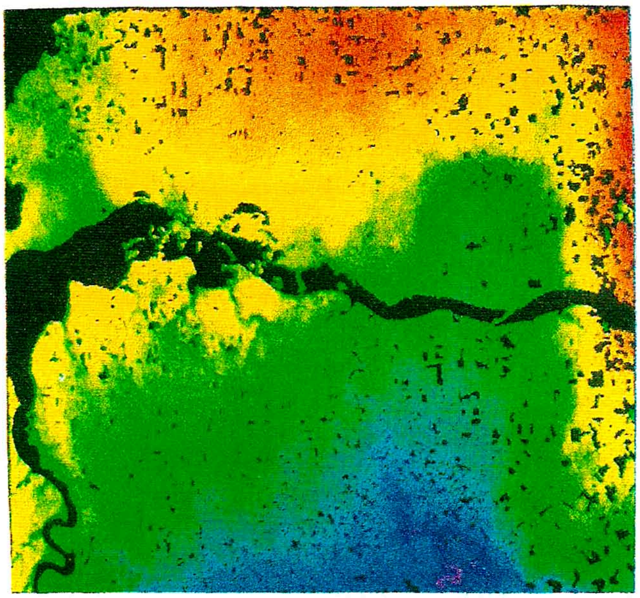

Fig. 5 - Original Phase Image of Ukraine.

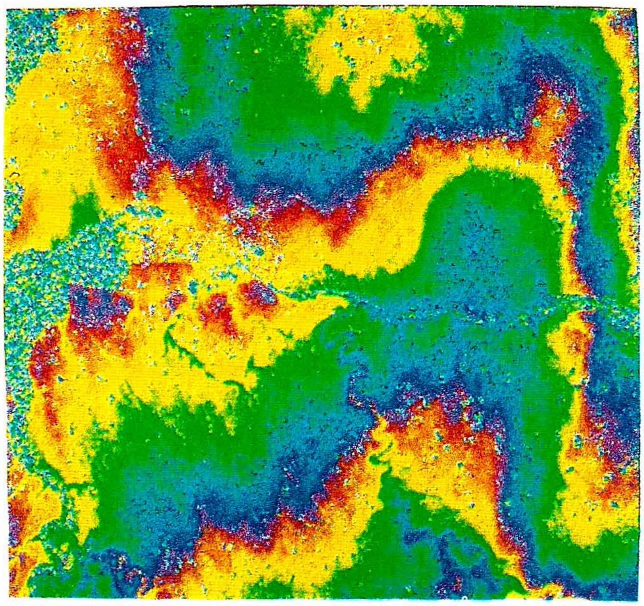

Fig. 7 - developed phases with unreliable phase areas filled everywhere it may be done coherently with the neighbouring areas information.

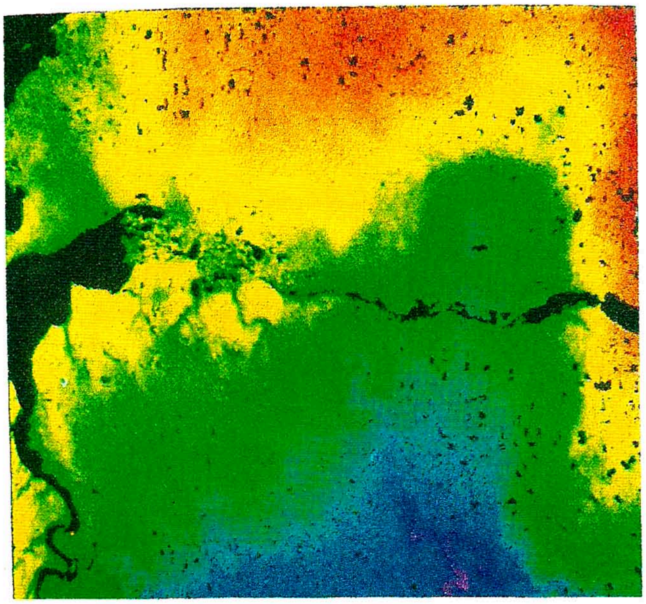

Fig. 6 - Developed phases within reliable areas only (the phase has been normalised between its min and max values, black areas are unreliable phase areas).

second in the east of the Dniepr River, and the third in-between the two rivers. There is no guaranteed relationship between both parts, because of the continuous incoherent areas of the rivers. But a reasonable assumption would be that no important phase difference appears between the banks of a river. This assumption has been made in the choice of colors for the phase coding.

The method which is presented here has not be quantitatively tested against real ground values. At first, as presented on the illustrations, we only remain in the phase domain and never draw a DEM map. Also our knowledge on the ground only relies on a poor map which doesn't provide enough elevation information. The quality control of the method clearly remains a task to be made now.

This method doesn't work everywhere. It relies on good data, with well contrasted fringes and a reasonnable amount of non-reliable areas. In areas with mountains and cliffs, different decisions have to be taken concerning the masked areas (lay-overs for instance may create important phase discontinuities, but they do not degrade the Ukraine area, and thus are not introduced in the presentation made here). This is the present stage of the work to make a catalogue of the different possible situations, according to the geographical context. Are taken into account the geological landscape, climatic conditions, atmospheric information and agricultural and vegetation information. But, even with improved

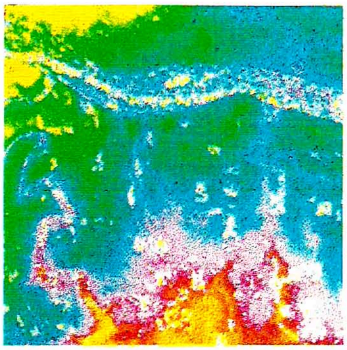

Fig. 8 - enlargement of a small area of the central part of the origial phase image.

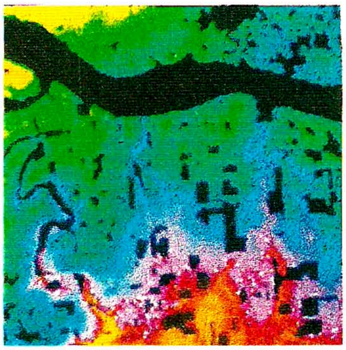

Fig. 9 - the developped phase in reliable areas only of the subimage.

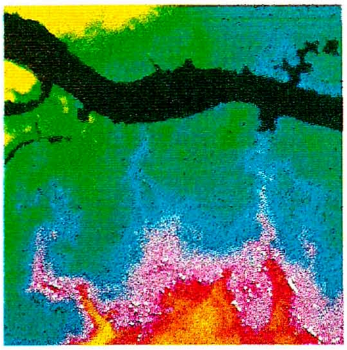

Fig. 10 - the unreliable areas are filtered by polynomial interpolation.

Fig. 11 - the final developped phase with a Markov Random Field filtering after polynomial interpolation.

criteria to detect unreliable areas, our experiments on different landscapes are not always as demonstrative as on Ukraine, and we still face poor results under adverse conditions.

Nevertheless, since good quality data are more and more frequent due to a better control that exists on the interferometric production, we are convinced that automatic phase unwrapping will be generalized. This method provides excellent results when these conditions are met. At first it appears very important to separate the possible sources of confusion when unwrapping the phase. This is done by our efficient unreliable phase area detection stage. Thus our method takes advantage of the good coherence to develope locally phases. This stage is fast and efficient and may be performed in parallel to increase the speed of the process. Then, when development is less easy, the decision to add 2π is taken not on a local basis, but from a regional measure, improving its reliability. At last, region filling is made based on a modelization of the object after it has been identified from its signature (SAR value, correlation, phase information). This stage could clearly benefit from a deeper knowledge of the region to be processed, and with a simple man/machine interface could take advantage of the knowledge of a supervising expert interpreter.

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